BBC RD 1977/39

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DIRECT SATELLITE BROADCASTING: intermodulation between multiple f.m. sound subcarriers

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October 1977

BBC RD 1977/39
UDC 621.396.946:
621.391.822.4

DIRECT SATELLITE BROADCASTING: INTERMODULATION BETWEEN MULTIPLE F.M. SOUND SUBCARRIERS

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Summary

The report describes an experimental study of the effects of intermodulation between multiple f.m. sound subcarriers. Such a system could provide supplementary sound channels for satellite broadcasting, where the subcarriers would frequency-modulate a 12 GHz carrier.

The report concludes that a system using twelve f.m. sound subcarriers is very sensitive to intermodulation. To avoid an audible impairment in a practical system, the levels of the twelve subcarriers would have to be relatively low and, consequently, the signal-to-noise ratio that could be achieved would not be very high. The report suggests that an investigation of other possible systems using digital techniques would be worthwhile.

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October 1977

(EL-133)

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1. Introduction

In the direct satellite broadcasting system that is currently being planned, the television signal frequency-modulates a carrier in the 12 GHz band. For System I television, the television signal would be pre-emphasised according to the CCIR 625-line characteristic[1] and would deviate a 12 GHz carrier by 13 MHz, peak-to-peak.[2] Each television signal would be accompanied by an f.m. sound subcarrier at 6 MHz which would in turn deviate the main carrier by ± 2·8 MHz peak.[2] The required radio frequency bandwidth for such a signal is about 27 MHz.

Recently, consideration has been given to methods of providing supplementary high-quality sound channels. These supplementary channels would probably be used to provide radio services, but in some cases, they might be used for a second-language sound-track accompanying a television programme.

It would be an advantage if the supplementary sound channels used a modulation system similar to that proposed for the satellite television service. A domestic receiver could then be designed to handle both types of signal. Furthermore, the sound signals could use the same satellite-borne transmitters as the television signals.

In the search for a fully compatible system, various proposals for providing the supplementary sound channels have been made and are being examined by EBU Study Group K3. In the simplest of these proposals, a 12 GHz carrier would be frequency-modulated by a series of subcarriers whose frequencies lay within a bandwidth of about 6 MHz, similar to the normal video bandwidth; each of the subcarriers would be frequency-modulated by a sound signal. F.M. sound signals of this form could be received relatively simply. Other proposals recommend the use of digital sound modulation systems which might require a more complex receiver.

One problem associated with a multiple f.m. subcarrier system is the fact that significant intermodulation between the subcarriers will produce an audible impairment of the individual sound signals. Intermodulation is particularly likely to arise due to the band-limiting action of the i.f. filter in the domestic receiver, as well as non-linearity of the transfer characteristic of the f.m. discriminator normally used to demodulate a television signal.

The level of intermodulation products can be made insignificant if the amplitude of the individual subcarriers is reduced sufficiently. However, this will increase the effect of thermal noise added by the r.f. stages of the domestic receiver. There is, therefore, a compromise level for the subcarriers which will give the best sound quality.

This report describes an experimental study of the effects of intermodulation between 12 f.m. subcarriers. The parameters of the experimental system were chosen to be compatible with a direct satellite broadcasting television service of the type outlined earlier.

The aim of this work was to discover if a multiple f.m. subcarrier system could provide supplementary sound channels of sufficient quality. The effects of non-linearities introduced by the domestic receiver's i.f. filter and f.m. demodulator were taken into account.

2. Basic system parameters

2.1. General

The multiple f.m. subcarrier system was designed to be compatible with the system planned for television broadcasting. The characteristics of the television system that have a bearing on the performance of a multiple subcarrier system are listed in Table 1.

TABLE 1

Parameters of satellite broadcasting system for television

Received carrier-to-noise ratio exceeded for 99% of the time	14·1 dB
R.F. bandwidth (–3 dB) of domestic receivers	27 MHz
Frequency deviation of carrier by television signals	13 MHz peak-to-peak/volt
Video bandwidth (including 6 MHz sound subcarrier)	6 MHz

Within the basic format of a multiple f.m. subcarrier system, there are numerous variants. The number of subcarriers, the frequency deviation of each subcarrier, their frequency-spacing and amplitudes can all be varied. For any particular number of subcarriers, there will be an optimum set of parameters which will give the best audio signal-to-noise ratio. However, since all the parameters are interdependent, it is a complicated task to find the optimum system.

The main parameters of the experimental system using twelve f.m. subcarriers are listed in Table 2. This system may well not be the optimum; however, it provided a useful starting point for this investigation. The

TABLE 2

Parameters of experimental 12 f.m. sound subcarrier system

Peak frequency deviation of each subcarrier	± 75 kHz
Pre-emphasis time constant	50 μs
Frequency spacing between subcarriers	295 kHz

Subcarrier number	1	2	3	4	5	6	7	8	9	10	11	12
Subcarrier frequency, MHz	1·0325	1·3275	1·6225	1·9175	2·2125	2·5075	2·8025	3·0975	3·3925	3·6875	3·9825	4·2775
Peak frequency deviation of main carrier by subcarrier, MHz	"	"	"	"	"	"	"	"	"	"	"	"

main parameters are similar to those suggested by other sources.

In the following subsections, the way in which the individual parameters were chosen is described in some detail.

2.2. Characteristics of each subcarrier

The subcarrier modulation was somewhat arbitrarily chosen to be the same as that of a conventional Band II v.h.f./f.m. transmission. The peak deviation of each subcarrier was ± 75 kHz and 50 μs pre-emphasis was used. With these characteristics, the 12 subcarriers can fit quite comfortably into the nominal video bandwidth of 0 to 6 MHz.

Each of the subcarriers was modulated by a monophonic audio signal. Stereophonic operation using the conventional pilot-tone system would give an unacceptably low signal-to-noise ratio; if stereophony were desired, two subcarriers could be used.

2.3. Deviation of main carrier by each subcarrier

One of the aims of the multiple f.m. subcarrier proposal is to provide supplementary sound channels with a very good signal-to-noise ratio. The target was an audio signal-to-weighted-noise ratio,[3] greater than 60 dB for 99% of the time. This compares with a 50 dB signal-to-weighted-noise ratio[3] for the sound channel accompanying a television signal.

The audio signal-to-noise ratio is set by the frequency deviation of the main carrier by each subcarrier and the main-carrier-to-noise ratio before demodulation (see Table 1). After demodulation of the main carrier, the baseband noise spectrum will be triangular. If each subcarrier is to give identical performance, the amplitude of each subcarrier must be proportional to its frequency. This is equivalent to saying that each subcarrier must phase-modulate the main carrier by the same amount.

It is shown in Appendix A, that the audio signal-to-weighted-noise ratio[3] will exceed 60 dB for 99% of the time if each subcarrier phase-modulates the main carrier by about ± 1 radian peak. Hence, the peak frequency deviation of the main carrier by each subcarrier equals the subcarrier frequency. This level of each subcarrier was the starting point for the investigation described here. But, as is shown later, for the system to be compatible with satellite television broadcasting, the level of each subcarrier would have to be reduced significantly.

2.4. Frequencies of subcarriers

2.4.1. Choice of spacing

It is desirable for the frequency spacing of the subcarriers to be as low as possible so that the multiple f.m. subcarrier signal occupies the minimum baseband bandwidth. The spacing cannot be made too low, however, because of interference from the adjacent subcarriers.

It is reasonable to assume that a domestic receiver for the multiple subcarrier signal would have similar selectivity to a conventional v.h.f./f.m. receiver. The modulation parameters of the systems are the same, and receiver manufacturers would no doubt use the same type of i.f. filter in both cases.

The CCIR have published curves[4] for v.h.f./f.m. transmissions with a maximum frequency deviation of ± 75 kHz, which show the relationship between the spacing of wanted and interfering signals and the required radio-frequency protection ratios. In the present application, adjacent subcarriers would be of approximately equal amplitude and only their spacing can be varied. From the CCIR curves,[4] a spacing of 260 kHz would give a wanted audio signal-to-weighted-noise ratio[3] of about 50 dB. However, since the subcarrier system is designed to give an audio signal-to-weighted-noise ratio of better than 60 dB a slightly greater spacing is required.

The frequency spacing of the subcarriers was finally chosen to be 295 kHz.

2.4.2. Choice of frequency

Non-linearities in the broadcast chain will generate unwanted intermodulation between the twelve subcarriers. The major cause of non-linearity was expected to be the band-limiting action of the i.f. filter within the domestic receiver. The effects of any unwanted intermodulation products can be minimised by a careful choice of the exact subcarrier frequencies.

The most common intermodulation products caused by non-linearities are of second and third orders. The second-order intermodulation products from two coherent signals with frequencies f_1 and f_2 lie at $f_1 \pm f_2$. The third order products for the same two signals lie at $2f_1 \pm f_2$ and $2f_2 \pm f_1$. Third order products can also be generated where three signals are involved and the products lie at $f_1 \pm f_2 \pm f_3$.

Since the twelve subcarriers are spaced by 295 kHz, their frequencies can be written as shown below, where f_0 equals the frequency of the lowest subcarrier.

$$\text{frequencies of subcarriers} = f_0 + n(0{\cdot}295)\,\text{MHz} \qquad n = 0, \ldots .\,11 \qquad 1)$$

The second-order intermodulation products will therefore lie at:—

$$\begin{aligned} \text{frequencies of second-order intermodulation products} &= 2f_0 + p(0{\cdot}295)\,\text{MHz} \quad p = 0, \ldots 22 \qquad 2) \\ &\text{and } q\,(0.295)\,\text{MHz} \quad q = 0, \ldots .\,11 \qquad 3) \end{aligned}$$

Similarly the third-order intermodulation products will lie at:—

$$\begin{aligned} \text{frequencies of third-order intermodulation products} &= 3f_0 + r\,(0{\cdot}295)\,\text{MHz} \quad r = 0, \ldots .\,33 \qquad 4) \\ \text{and } &f_0 + s(0{\cdot}295)\,\text{MHz} \quad s = -11, \ldots 0, \ldots \ldots 22 \qquad 5) \end{aligned}$$

Comparing equation 5 with equation 1, it can be seen that, independent of the value of f_0, some third-order intermodulation products will always coincide with some of the subcarriers.

However, by a suitable choice of f_0, the second-order intermodulation products can be made to fall between the subcarriers; this is achieved if $f_0 = ([2m + 1]/2) \times 0{\cdot}295$ MHz (m = 0, 1, etc.). Since the second-order products normally have the largest amplitude, it is an advantage if they fall between the subcarriers.

The final choice of the lowest subcarrier frequency was influenced by the effects of the third-order products of the type given by equation 5. As discussed in Section 2.3., the amplitudes of each of the subcarriers are arranged to be proportional to their individual frequencies. Thus, the lowest frequency subcarrier has the smallest amplitude and therefore is the most vulnerable to third-order products. If the frequencies of all the subcarriers are lowered, the demodulated amplitude of the lowest subcarrier is lowered and the third-order intermodulation products become more damaging. On the other hand, if the frequencies of the subcarriers are raised, their amplitudes increase and the level of the intermodulation products will increase. These two effects act in opposition and there is an optimum set of frequencies for the subcarriers which minimises the effects of the third-order intermodulation products. In Appendix B it is shown that, in theory, the optimum frequency for the lowest subcarrier is about 1 MHz.

The frequency of the lowest subcarrier was finally chosen to be 1·0325 MHz (3·5 x 295 kHz). The frequency of the highest subcarrier is then 4·2775 MHz.

3. Experimental equipment

3.1. General

A block schematic diagram of the experimental arrangement used for studying intermodulation between the f.m. subcarriers is shown in Fig. 1.

For convenience, the experiments were conducted at an intermediate frequency of 70 MHz.

The bandpass filters labelled A and B in Fig. 1 were designed to simulate the i.f. filter in a domestic receiver.[5] Both filters had a –3 dB bandwidth of 27 MHz. Filter A was equivalent to a 4-section bandpass filter and Filter B a 6-section filter. The amplitude and group-delay responses of the two filters are shown in Fig. 2. Neither of the filters was group-delay corrected.

In the following sub-sections, a brief description is given of each of the units that make up the experimental arrangement shown in Fig. 1.

3.2. Generation of 12 f.m. subcarriers

The experimental arrangement for generating the twelve subcarriers is shown in Fig. 3.

Referring to Fig. 3, twelve independent oscillators whose frequencies lay within an octave of bandwidth were built and they are shown in the photograph above the block diagram. This method was chosen because it is difficult to construct oscillators with low harmonic distortion and if all the oscillator frequencies are within one octave the oscillator harmonics lie outside the band of interest. The frequency spacing between the oscillators was 295 kHz. Each one could be frequency-modulated with a peak deviation of ± 75 kHz and 50 μs pre-emphasis was built-in. The amplitude of the output from each oscillator could be adjusted using a potentiometer.

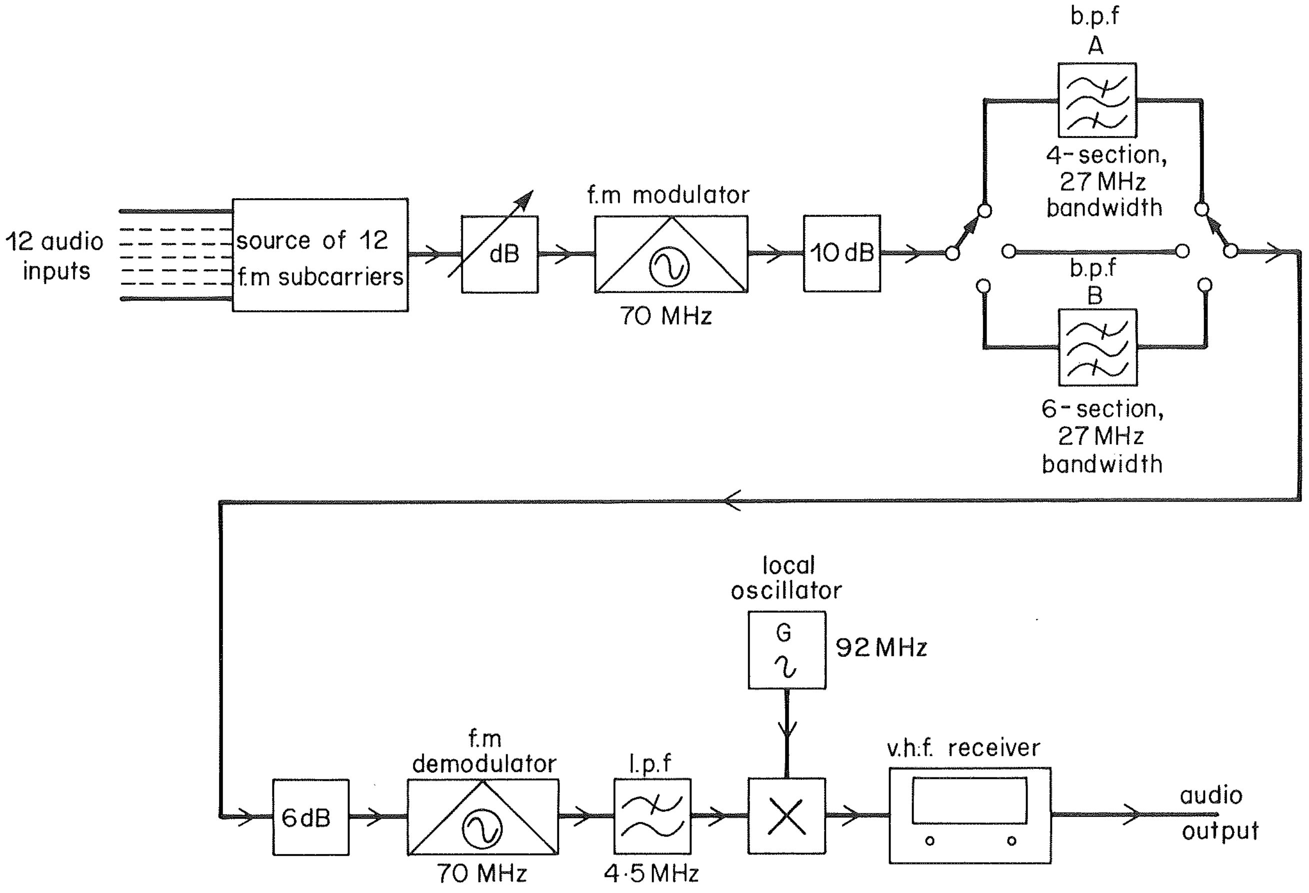

Fig. 1 - Experiment arrangement for studying intermodulation between f.m. subcarriers

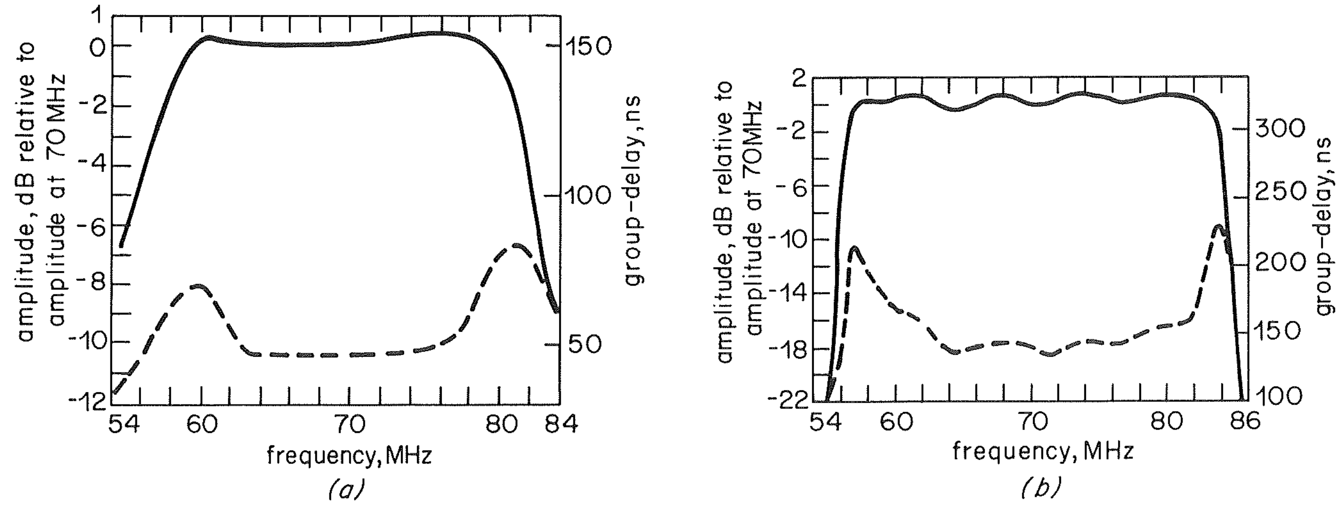

Fig. 2 - Amplitude and group-delay responses of i.f. filters

(a) Filter A, 4-sections
(b) Filter B, 6-sections

——— amplitude responses
– – – group-delay responses

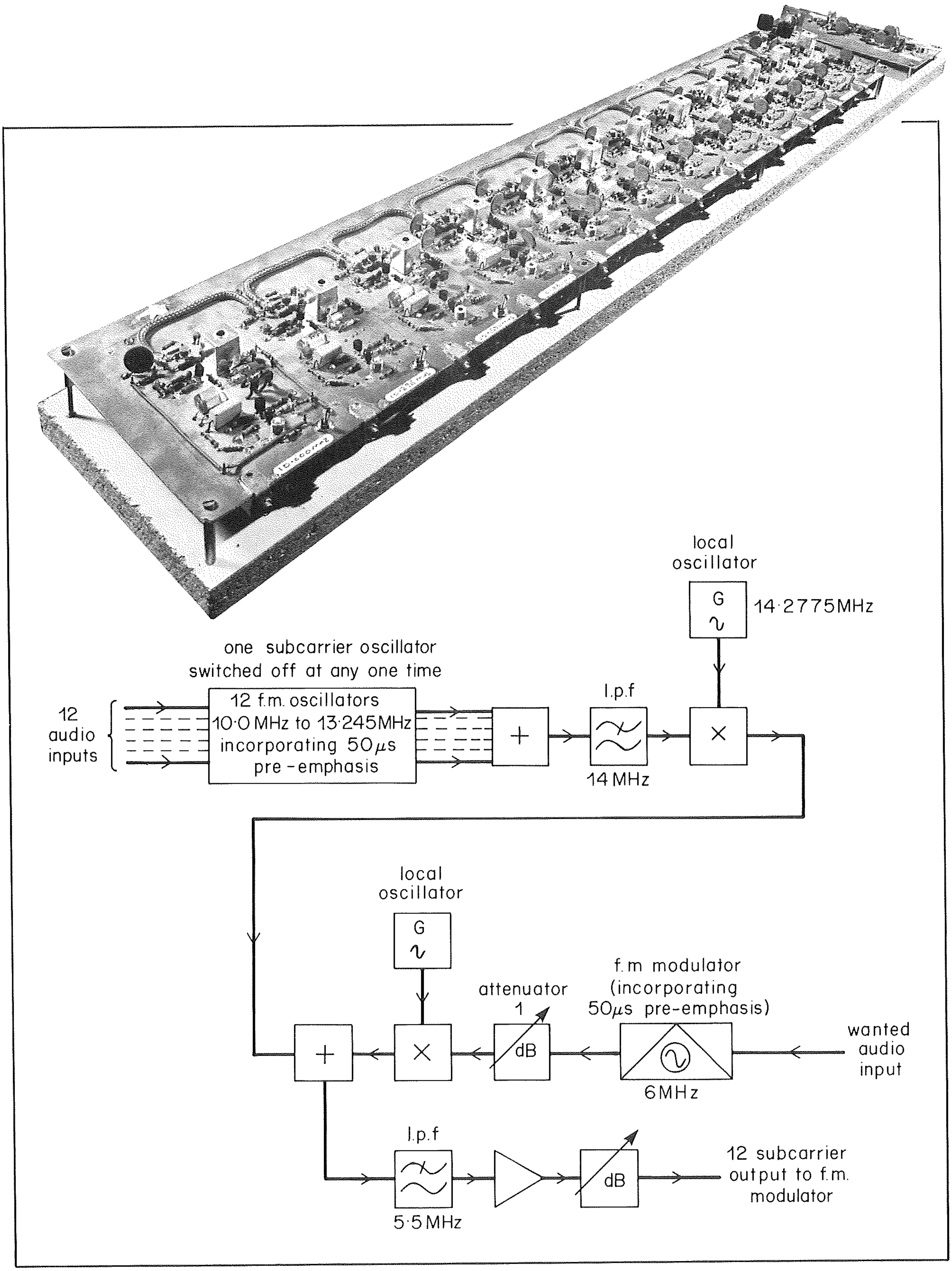
local oscillator
G
14·2775MHz
one subcarrier oscillator switched off at any one time
12 audio inputs
12 f.m. oscillators 10·0 MHz to 13·245MHz incorporating 50μs pre-emphasis
+
l.p.f
14 MHz
×
local oscillator
G
f.m modulator (incorporating 50μs pre-emphasis)
attenuator 1
dB
6MHz
wanted audio input
+
×
l.p.f
5·5 MHz
dB
12 subcarrier output to f.m. modulator

Fig. 3 - Experimental arrangement for generating twelve subcarriers

The outputs from the twelve oscillators were summed and then frequency-shifted to produce twelve f.m. subcarriers at the frequencies shown in Table 2.

Although each of the oscillators could be frequency-modulated up to ± 75 kHz deviation, their transfer characteristic was not particularly linear. The non-linearity gave rise to just-perceptible distortion of the audio signal after demodulation. This meant that the signals from the twelve oscillators could be used only to produce the interfering subcarriers. The wanted subcarrier was produced using a separate high-quality 6 MHz frequency modulator. This modulator gave very little distortion of the audio signal and an audio signal-to-weighted-noise[3] ratio of better than 70 dB. The output from the 6 MHz modulator was frequency-shifted so as to lie at one of the subcarrier frequencies shown in Table 2 and the appropriate oscillator from the group of twelve was switched off. To avoid any possibility of signal breakthrough, this switching was done by disconnecting the power supply to the oscillator.

The wanted subcarrier was then combined with the other eleven subcarriers and the signal lowpass filtered at 5·5 MHz before being applied to the 70 MHz frequency modulator. The relative amplitudes of the eleven interfering subcarriers were set by potentiometers. The relative amplitude of the wanted subcarrier was set by the variable attenuator labelled 1 in Fig. 3.

The subcarrier frequencies were accurate to within ± 5 kHz and their amplitudes were accurate to within ± 0·5 dB.

The level of unwanted intermodulation products measured at the input to the 70 MHz modulator was lower than −55 dB, compared with the level of the smallest subcarrier.

3.3. 70 MHz f.m. modulator

Measurements of the statistics of the multiple f.m. subcarrier signal (see Section 4) showed that, at the designed modulating signal level, the main carrier could occasionally be deviated by ± 30 MHz peak. The r.f. channel bandwidth for the satellite broadcasting system is only 27 MHz and the action of any band-limiting filters will distort the multiple subcarrier signal. However, since the high peak deviations occur for very short periods of time, the precise effects of any band-limiting filters could not be deduced.

In order to study the above effects, it is necessary to use an f.m. modulator and demodulator (modem) capable of handling high peak deviations. The f.m. modem that would normally have been used is a commercial unit designed for s.h.f. link applications. This equipment can handle signals with peak-to-peak deviations of about 25 MHz, which has in the past been adequate for television experiments. However, for the multiple subcarrier signal, the deviation range of the modem had to be extended.

This subsection and the one that follows, briefly describe the modifications made to the f.m. modem in order to increase its deviation range.

A block schematic diagram of the modified 70 MHz f.m. modulator is shown in Fig. 4.

Referring to this Figure, the output from the commercial modulator was frequency-multiplied by four The frequency deviation of the resulting 280 MHz signal is four-times that of the 70 MHz signal. The frequency multiplier was formed from two two-transistor full-wave rectifiers in tandem. The output signal from the frequency multiplier contained unwanted harmonics which were removed by the 220-340 MHz bandpass filter.

The 280 MHz f.m. signal was then frequency-shifted back to 70 MHz using a mixer fed by a local oscillator at 210 MHz. The output from the mixer was passed through a 25-100 MHz bandpass filter to remove unwanted mixing

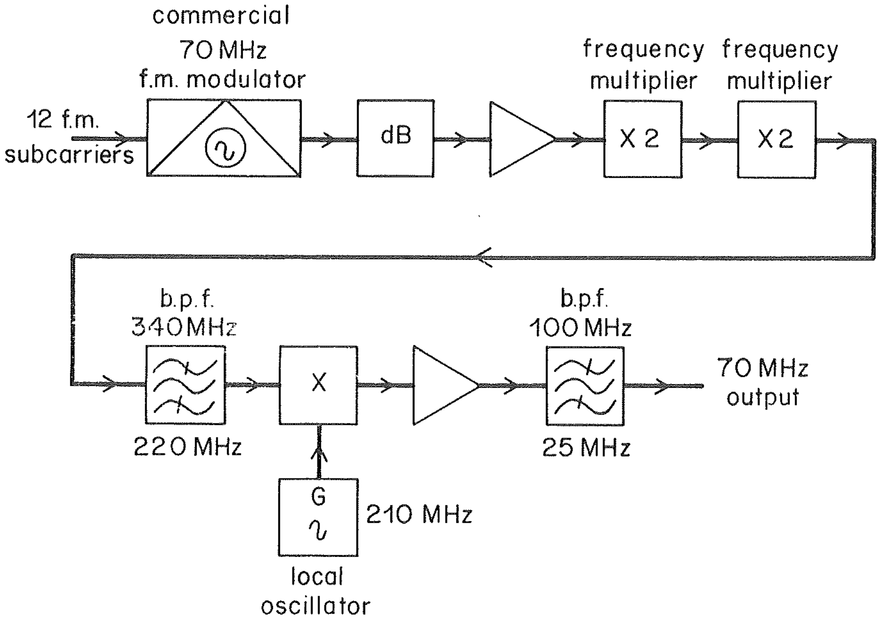

Fig. 4 - 70 MHz f.m. modulator

products.

Using the arrangement of Fig. 4 a 70 MHz signal was produced that could be frequency-modulated with reasonable linearity up to peak deviations of ± 25 MHz.

3.4. 70 MHz f.m. demodulator

It was inconvenient to modify the commercial 70 MHz f.m. demodulator and a separate wide-deviation demodulator was constructed. A block diagram of this demodulator is shown in Fig. 5.

Referring to Fig. 5, the incoming 70 MHz f.m. signal was first limited, and then frequency-divided by two. The divided output is a signal of 35 MHz whose frequency deviation is half that of the incoming signal.

The remainder of the circuitry forms a delay-line discriminator whose principle of operation is as follows. The output from the frequency divider drives two signal paths whose time delays differ by an amount corresponding to 90° phase shift at 35 MHz. The delayed path was made using a short length of coaxial cable. The outputs from the two signal-paths drive the two inputs of an exclusive-OR gate. The exclusive-OR gate acts as a phase-detector whose two output voltage levels are symmetrical about earth and whose mean output voltage is proportional to the phase difference between its inputs. The mean output voltage is zero when there is a 90° phase difference between the inputs. Since the phase difference between the inputs to the gate varies linearly with frequency, the circuit acts as a frequency discriminator. The balanced output from the gate was amplified by a video amplifier.

The f.m. demodulator had a transfer characteristic which was reasonably linear for f.m. signals with frequency deviations up to ± 25 MHz. The limiter at the input to the circuit had a dynamic range of about 60 dB.

3.5. Subcarrier demodulator

The individual f.m. subcarriers were demodulated using a commercial high-quality v.h.f./f.m. receiver. The r.f. selectivity of this receiver is very good, its audio distortion is low and it can achieve audio signal-to-weighted-noise ratios[3] of about 70 dB.

The twelve f.m. subcarriers at the output of the 70 MHz f.m. demodulator, were frequency-shifted to about 95 MHz before being applied to the input of the v.h.f. receiver. The frequency shifter used a conventional diode-mixer circuit.

4. Experimental work

4.1. Measurements of the amplitude distribution of the multiple subcarrier signal

From the figures given in Table 2, it can be seen that if all the subcarriers were to add up so that their peak values coincided the signal would deviate the main carrier by ± 31·9 MHz. This is the maximum possible frequency deviation of the main carrier.

On the other hand, the r.m.s. frequency deviation of the main carrier is given by:—

r.m.s. frequency deviation =

$$= \sqrt{\sum_{n=1}^{12} \frac{\left[\text{peak frequency deviation due to } n^{\text{th}} \text{ subcarrier}\right]^2}{2}}$$

$= 7{\cdot}0$ MHz

The r.f. channel bandwidth allowed for the signal is 27 MHz. If the deviation of the main carrier approached its maximum possible value (± 31·9 MHz), the multiple subcarrier signal would be distorted, the amount of the distortion depending on the duration of the peak excursion. But if, the deviation of the main carrier never greatly exceeded the r.m.s. frequency deviation, the r.f. signal would fit comfortably within the channel bandwidth. In this case, there would be very little distortion of the multiple subcarrier signal.

In order to find out which of the above cases was most representative, measurements were made of the amplitude distribution of the multiple subcarrier signal. The experimental set-up is shown in Fig. 6.

Referring to this Figure, the twelve unmodulated subcarriers were applied together to one input of a high-

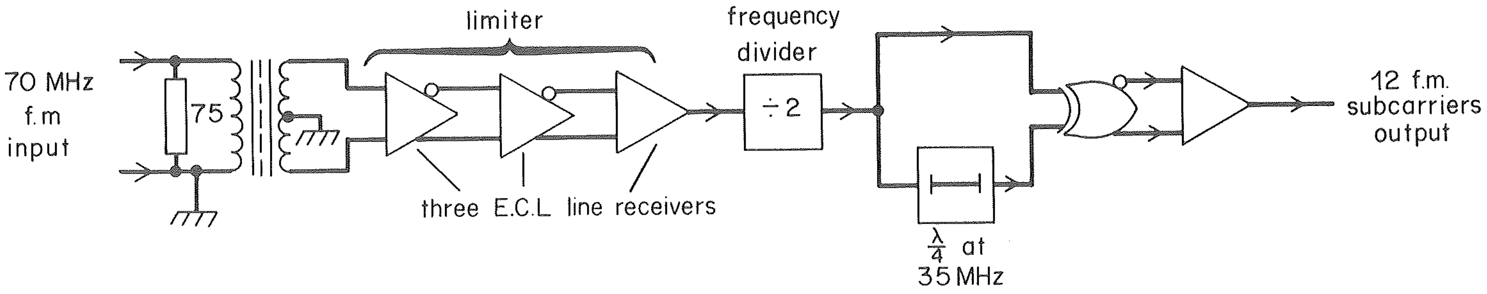
limiter
frequency divider
70 MHz f.m input
75
÷2
three E.C.L line receivers
$\frac{\lambda}{4}$ at 35 MHz
12 f.m. subcarriers output

Fig. 5 - 70 MHz f.m. demodulator

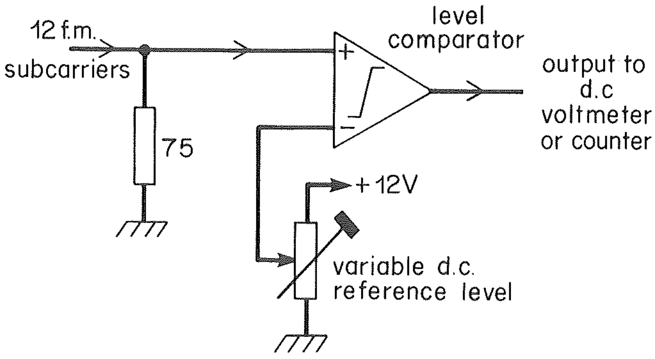

Fig. 6 - Experimental set-up for measuring the amplitude distribution of multiple subcarrier signal

speed level comparator. The other input was connected to a variable d.c. reference level obtained from a potentiometer. Whenever the level of the subcarrier signal exceeded the d.c. reference level, the output of the level comparator would change from its 'low' to its 'high' state and remain there as long as the subcarrier signal was above the reference level.

By measuring the mean output voltage of the level comparator (using a d.c. voltmeter) the percentage of the time that the multiple subcarrier signal spends above the d.c. reference level could be deduced. The exact formula is given below.

$$\text{percentage time that subcarrier signal exceeds d.c. reference level} = \frac{V_M - V_{OL}}{V_{OH} - V_{OL}} \times 100\%$$

where V_M = mean output voltage of comparator

V_{OL} = output voltage of comparator in 'low' state

V_{OH} = output voltage of comparator in 'high' state

The results of the experimental measurements are plotted in Fig. 7. The value of the d.c. reference level at one input to the level comparator has been plotted in terms of the frequency deviation of the main carrier which it represents. Also shown in this Figure is a plot for a Gaussian signal. This curve has been drawn so that the r.m.s. value of the Gaussian signal corresponds to the r.m.s. frequency deviation due to the subcarrier signal.

It can be seen from Fig. 7, that the amplitude distribution of the subcarrier signal is very similar to a Gaussian distribution; the difference corresponds to less than 1 dB in terms of frequency deviation. Bearing in mind the simplicity of the experiments, it is quite possible that the multiple subcarrier signal has Gaussian statistics over the range of amplitudes shown in Fig. 7. When the waveform of the summed subcarriers is viewed on an oscilloscope, it has the appearance of thermal noise. The waveform did not change appreciably when the subcarriers were individually frequency-modulated and the results of Fig. 7 should also be valid in this case.

The experiment described above was found to become inaccurate when the multiple subcarrier signal spent very little time above the d.c. reference level. However, by viewing the signal on an oscilloscope, it could be seen that the signal did reach much higher levels than those shown in Fig. 7. A further experiment was therefore devised. The experimental arrangement was the same as before except that the output signal from the level comparator was connected to a digital counter. The counter incremented its count by one every time the level comparator changed from its 'low' to its 'high' state.

The results of this experiment are shown in Fig. 8. As before, the d.c. reference level at one input to the level comparator has been plotted in terms of the frequency deviation which it represents. From Fig. 8, it is clear that the multiple subcarrier signal approached its maximum possible value quite frequently; for example, it came within 2 dB of the maximum approximately 300 times per second. The duration of each of these excursions was probably of the order of a few tens of nanoseconds.

The results of Fig. 8 also show that the main carrier would be deviated outside the channel bandwidth (27 MHz wide) more than 10^6 times per second. It was expected that these peak excursions would be grossly distorted by the i.f. filter in the domestic receiver and that the twelve audio signals would be impaired as a result though the degree of impairment was unknown.

4.2. Measurement of levels of intermodulation between subcarriers

The aim of these tests, was to determine the maximum level at which the group of subcarriers could modulate

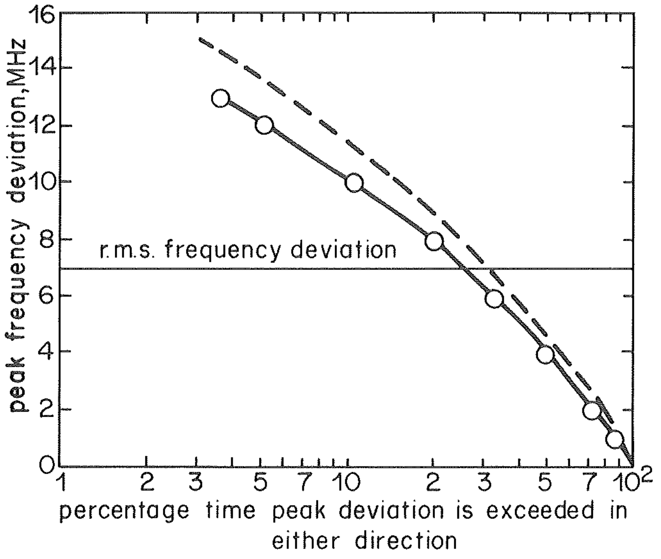

Fig. 7 - Amplitude distribution of multiple subcarrier

○—○ measured values
— — — Gaussian distribution

the main carrier without perceptible intermodulation between them. The tests were done using the arrangement shown in Fig. 1. The levels of the individual subcarriers were set to be proportional to their frequencies and their combined level was set using the variable attenuator shown in Fig. 1.

The quality of the demodulated sound signals was judged subjectively by two experienced engineers using a high-quality monitoring loudspeaker. Impairments of the audio signal were graded using the CCIR 5-point impairment scale.[6]

A preliminary experiment was conducted to find out which of the subcarriers was most affected by any intermodulation products. The twelve unmodulated subcarriers were applied to the input of the 70 MHz f.m. modulator and the bandpass filter labelled 'A' in Fig. 1 (see Section 3.1.) was placed in circuit. The subcarrier demodulator was tuned to subcarrier Number 6 in Table 2. As the level of the combined subcarriers was gradually increased, a series of whistles or "birdies" could be heard. When these whistles had become clearly audible the subcarrier demodulator was tuned to the other subcarriers in turn.

The lowest-frequency subcarrier was judged to be the most affected by the intermodulation products, though the difference between subcarriers was not very great. This result was not unexpected since the lowest-frequency subcarrier had the smallest amplitude. In all subsequent tests, only the quality of the lowest-frequency subcarrier was monitored; this subcarrier was generated using the high-quality 6 MHz frequency modulator described in Section 3.2.

A further preliminary test was conducted to study the effects of modulating the other eleven subcarriers whilst listening to the lowest-frequency subcarrier. When the other subcarriers were modulated by a random selection of programme material, this tended to break up the whistles in the wanted channel and cause them to sound more like random noise. Subjectively, the effect of the whistles was more annoying than the noise-like effects obtained when the other subcarriers were modulated. In all subsequent tests, the lowest-frequency subcarrier was the only one that was modulated.

In the final test, the lowest-frequency subcarrier was modulated by a speech passage taken from a news broadcast. This programme material was chosen since it contained many pauses which would tend to show up any intermodulation products. The speech signal was pre-emphasised with the standard 50 μs time-constant and deviated the wanted subcarrier by ± 75 kHz peak. A 5 dB allowance was made for pre-emphasis to ensure that high-frequency components did not overmodulate the subcarrier. The 5 dB allowance would probably not be needed in the future due to the increasing use of frequency-dependent programme limiters.

The impairment of the wanted subcarrier was judged for various levels of the multiple subcarrier signal. The effect of inserting either of the two i.f. filters (A or B in Fig. 1) was also studied. The results of the tests are shown in Fig. 9. The level of the subcarriers has been plotted with respect to a phase deviation of the main carrier by each subcarrier of ± 1 radian peak. The value of ± 1 radian peak, would give for each subcarrier an audio-signal-to-weighted-noise ratio[3] (in the absence of any intermodulation products) which exceeded 60 dB for 99% of the time. It can be seen that, even in the absence of an i.f. filter, the audio signal was impaired. The impairment was heard as a series of whistles or "birdies" whose level increased fairly rapidly with an increase in the level of the composite subcarriers. However, the addition of an i.f. filter could completely change the character of the impairment. When the deviation of the main carrier by each subcarrier was ± 1 radian peak, the introduction of either a 4-section of 6-section i.f. filter produced a very high noise level. This noise was described as being "granular" or "like the sound from a waterfall". As the level of the subcarriers was reduced, it was clear that the "granular" noise was made up from a series of impulses or clicks.

When the level of the subcarriers was reduced below

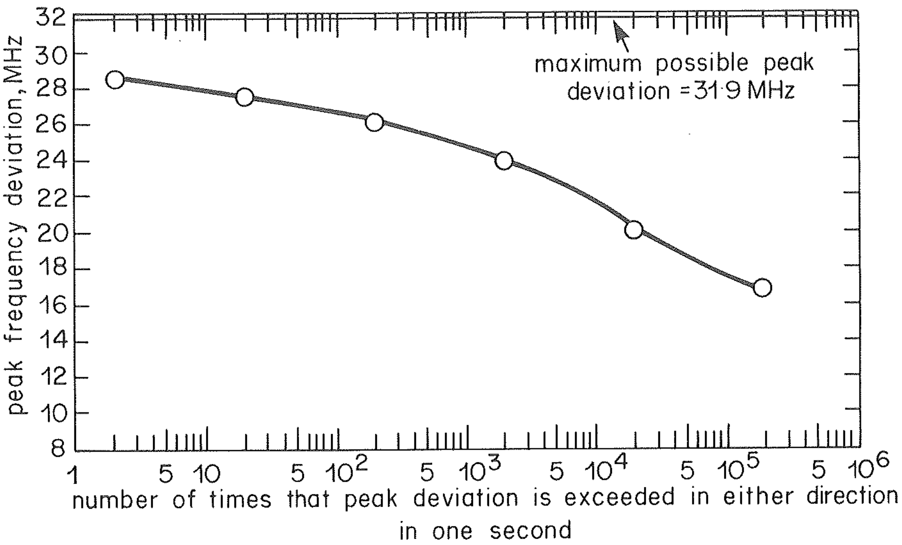

Fig. 8 - Statistics of peak excursions of multiple subcarrier signal

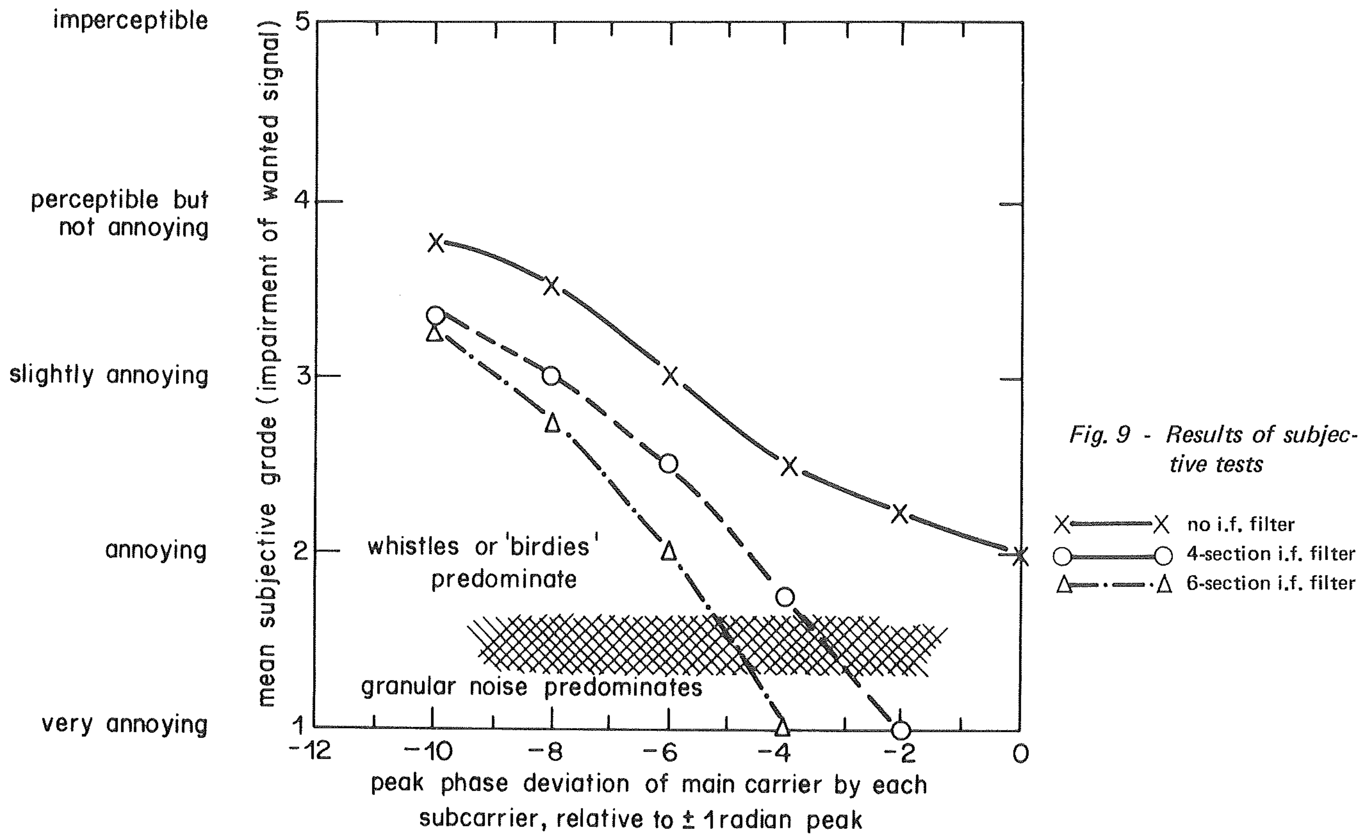

Fig. 9 - Results of subjective tests

a certain threshold value, the "granular" noise disappeared completely. There remained the whistles or "birdies", like those produced without an i.f. filter. The threshold condition for the "granular" noise corresponded to a deviation of the main carrier by each subcarrier of about –3 dB relative to ± 1 radian peak, for the 4-section i.f. filter. For the 6-section filter, the threshold was at about –5 dB relative to ± 1 radian peak.

5. Discussion of experimental results

The cause of the "granular" noise described in Section 4.2. can be found by considering the statistics of the multiple subcarrier signal. It was shown in Section 4.1. that a multiple-subcarrier signal of the kind used here occasionally reaches very high peak values. If these peaks are sufficiently great, the main 70 MHz carrier will be deviated outside the channel bandwidth of approximately 27 MHz and, when this deviation extends beyond the passband of the i.f. filter, the carrier level will be reduced. The amount of the reduction depends on the instantaneous frequency deviation and the steepness of cut-off of the i.f. filter. A significant reduction will produce an impulse of noise in each subcarrier channel and this is thought to be the cause of the "granular" noise described earlier.

In order to avoid the "granular" noise, the level of the composite subcarriers must be reduced until the peak deviation of the main carrier lies within the passband of the i.f. filter. The cut-off of the 6-section filter used in the tests was steeper than that of the 4-section filter and consequently the level of the subcarriers must be even lower when a 6-section filter is used.

When the level of the subcarriers is well below the "granular" noise threshold, the major source of impairment to the wanted audio signal is due to whistles and "birdies" (intermodulation products) believed to be caused by the non-linearity of the f.m. modem (see Fig. 9). The increase in impairment introduced by an i.f. filter is probably due to its variation in group-delay response. The variation in group-delay response of the 6-section filter is about twice that of the 4-section filter. This suggests that if the 4-section filter were group-delay equalised, the results when using such a filter would be even closer to those in the absence of the filter. An experiment to verify this was considered but eventually discarded, since the expected improvement of half a subjective grade is difficult to judge.

Because of the impairment introduced by the f.m. modem itself, it is very difficult to say what is the maximum level at which the twelve subcarriers could be transmitted without perceptible intermodulation between them. It is suggested that, if the f.m. modem were perfect and the i.f. filter was a 4-section type with a –3 dB bandwidth of 27 MHz, each subcarrier could deviate the main carrier by –6 dB with respect to ± 1 radian peak. This estimate is based on two factors. Firstly, at greater subcarrier levels, the impairment introduced by the i.f. filter predominates, as shown in Fig. 9. Secondly, it is suggested that if the f.m. modem were perfect, the impairment of the most afflicted subcarrier (the one with lowest frequency) would correspond to about grade 4 on the

CCIR 5-point scale. If the deviation of the main carrier by each subcarrier was −6 dB relative to ± 1 radian peak, the audio-signal-to-weighted-noise ratio[3] would exceed 54 dB for 99% of the time.

In arriving at the suggested level for the twelve subcarriers, it has been assumed that the f.m. modem would have near-perfect linearity. This has been assumed since the non-linearity of the f.m. modem used in the experiments was an important source of impairment. It is therefore of interest to examine the performance of the experimental f.m. modem in order to see what degree of linearity would be required in a practical multiple subcarrier system.

To this end, conventional measurements were made of the differential gain and phase distortion of the colour subcarrier when a video signal was passed through the f.m. modem. The test waveform was a 'staircase' with five steps and a colour subcarrier on each step; the staircase waveform occurred on every line of the television waveform. The video signal was pre-emphasised according to the CCIR 625-line characteristic[1] before modulation and de-emphasised after demodulation.

The measured levels of differential gain and phase distortion of the colour subcarrier for various carrier deviations are shown in Fig. 10. The frequency deviation scale corresponds to the point of unity gain on the pre-emphasis curve.

The results of Fig. 10 show that, in terms of television parameters, the f.m. modem had good linearity. For satellite television broadcasting, the carrier deviation will probably be 13 MHz peak-to-peak.[2] At this deviation, the f.m. modem was measured as having differential gain distortion of 2% and differential phase distortion of 1°. The effects of these levels of non-linearity would be imperceptible on a television picture. Moreover, this level of non-linearity would not cause significant intermodulation between the 6 MHz sound subcarrier and the colour subcarrier.

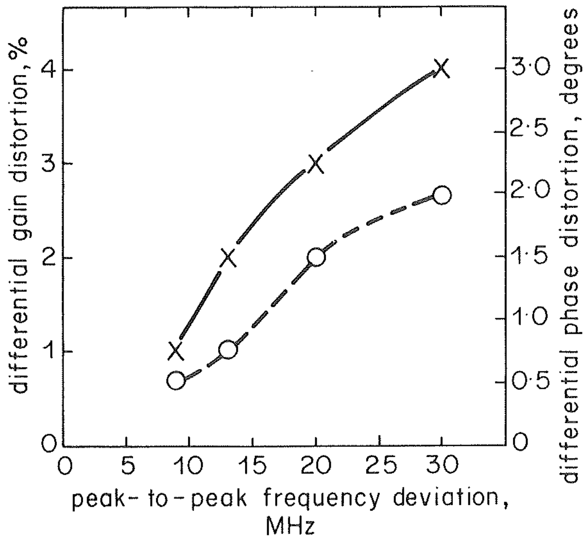

Fig. 10 - Differential gain and phase distortion of f.m. modem

X———X differential gain
○– – – –○ differential phase

From the above, it is clear that the quality that could be achieved when using a multiple subcarrier system is very sensitive to instrumental imperfections within the broadcast system. The weakest link in the chain is likely to be the domestic satellite receiver and the greater the performance demanded of the receiver the greater would be its cost.

There are two obvious changes that can be made to the multiple subcarrier system which would ease the problems of receiver design. The first of these would be to send the 12 subcarriers at a much lower level.

The second change that could be made to the subcarrier system would be to reduce the number of subcarriers. It is suggested that if the number of subcarriers was reduced to 8, an audio-signal-to-weighted[3]-noise ratio exceeding 60 dB could be achieved for 99% of the time.

One conclusion that can be drawn from this discussion is that the multiple f.m. subcarrier system is not well matched to the satellite broadcasting system currently envisaged. This disadvantage greatly outweighs the main attraction of the system, namely, its simplicity. It is worthwhile therefore to consider alternative systems which sacrifice simplicity in the interests of compatibility. For example, it is possible, using digital techniques, to fit up to 20 sound channels on one carrier and achieve an audio-signal-to-weighted-noise ratio[3] exceeding 60 dB. One technique that has been proposed[7] is to combine 20 p.c.m. sound channels into a serial bit-stream of about 7 Mbit/s which would, in turn, frequency-shift-key the main carrier. One disadvantage of using digital techniques is that the receiver must have a high-quality digital-to-analogue convertor (d.a.c.). At present, these devices are very expensive. However, it is likely that by the time satellite broadcasting comes into being, suitable cheap d.a.c.'s will be available.

6. Conclusions

It has been shown that a multiple subcarrier system for satellite broadcasting using twelve f.m. subcarriers is very likely to be unsatisfactory because of intermodulation between the subcarriers. The method is particularly sensitive to any non-linearities within the f.m. modulator and f.m. demodulator. The f.m. demodulator in a future domestic receiver is likely to be the most critical link in the chain; an f.m. demodulator that would be perfectly acceptable for the reception of television signals can produce unacceptable intermodulation between the twelve subcarriers.

If it can be assumed that domestic receivers would have a near-perfect f.m. demodulator, preceded by a 4-section group-delay equalised i.f. filter whose −3 dB bandwidth was 27 MHz, then a 12-subcarrier system could give an audio-signal-to-weighted-noise ratio[3] of greater than 54 dB for 99% of the time. If, on the other hand, a reasonable amount of non-linearity within the f.m. demodulator must be allowed, then an audio-signal-to-weighted-noise ratio[3] of about 50 dB could be obtained. Even at this level, the amount of non-linearity within the f.m. demodulator that can be tolerated is likely to be lower than can be tolerated by the television signal.

It has been suggested that other modulation systems using digital techniques would be capable of providing many more sound channels with better quality than the multiple f.m. subcarrier system. In the light of the results of the work described in this report, further investigation of other modulation systems would seem worthwhile.

7. References

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5. GILCHRIST, N.H.C. 1975. Satellite broadcasting: the effects of filter design upon the bandwidth and adjacent-channel separation requirements for f.m. television signals. BBC Research Department Report No. 1975/8.
6. CCIR Proceedings of the XIIIth Plenary Assembly, Geneva 1974, XI, Recommendation 500.
7. CCIR, Geneva 1976, Document No. 11/297-E, Report 215-3 (Rev. 76).

APPENDIX A

The relationship between audio-signal-to-noise ratio and subcarrier level

The multiple subcarrier system using twelve f.m. sound subcarriers is designed to give an audio-signal-to-weighted-noise ratio[3] which exceeds 60 dB for 99% of the time. For 99% of the time the received main-carrier-to-noise ratio in 27 MHz bandwidth will exceed 14·1 dB (see Table 1). The following analysis shows that, to meet the performance objective, each subcarrier must phase-modulate the main carrier with a peak deviation of ± 1 radian.

If the required audio-signal-to-weighted-noise ratio[3] is 60 dB, then the audio-signal-to-unweighted-noise ratio must be 69 dB. This assumes that the audio noise spectrum is triangular, prior to 50 μs de-emphasis.

De-emphasis improves the signal-to-noise ratio by 10·2 dB and hence the signal-to-noise ratio before de-emphasis is 58·8 dB.

The peak frequency deviation of each subcarrier is ± 75 kHz and hence the r.m.s. frequency deviation of each subcarrier due to the noise, is 60 Hz.

The r.m.s. frequency deviation of each subcarrier by the noise with 15 kHz audio bandwidth is given by

$$\text{r.m.s. frequency deviation of each subcarrier due to noise} = 60\ \text{Hz} = \frac{15 \times 10^3}{\sqrt{6}} \cdot \frac{1}{\sqrt{C_N}}\ \text{Hz} \quad \ldots.\ 1)$$

where C_N = ratio of subcarrier-power to noise-power, within ± 15 kHz of subcarrier rest frequency

The subcarrier-to-noise ratio can be derived from the parameters of the main carrier, and the level of each subcarrier. The baseband noise spectrum, after de-modulation of the main carrier, will be triangular. Hence, if each subcarrier is to give the same performance, its amplitude must be made proportional to its frequency. This is equivalent to saying that each subcarrier must phase-modulate the main carrier by the same amount. Let the peak phase deviation of the main carrier by each subcarrier equal ± m radians.

For the main carrier, when the carrier-to-noise ratio in 27 MHz bandwidth is 14·1 dB, the r.m.s. phase deviation of the carrier by the noise is given by:

$$\text{r.m.s. phase deviation of main carrier due to noise} = \frac{1}{\sqrt{2}}\ 10^{\frac{-14{\cdot}1}{20}}\ \text{radians}$$

$$= 0{\cdot}139 \text{ radians with a bandwidth of } 13{\cdot}5 \text{ MHz} \quad \ldots.\ 2)$$

Hence C_N, which equals the subcarrier-to-noise power ratio in ± 15 kHz bandwidth, is given by

$$C_N = \left[\frac{m}{\sqrt{2} \times 0{\cdot}139}\right]^2 \times \frac{13{\cdot}5 \times 10^6}{30 \times 10^3}$$

$$= m^2 \times 1{\cdot}165 \times 10^4 \quad \ldots.\ 3)$$

By substituting for C_N in equation 1), we find that

$$m = \frac{15 \times 10^3}{60\ [6 \times 1{\cdot}165 \times 10^4]^{1/2}}$$

$$= 0{\cdot}95 \text{ radians.} \quad \ldots.\ 4)$$

Hence, to achieve an audio-signal-to-noise ratio exceeding 60 dB for 99% of the time, each subcarrier must phase-modulate the main carrier with a peak deviation of about ± 1 radian.

APPENDIX B

Optimum subcarrier frequencies

As discussed in Section 2.4.2., there is an optimum set of frequencies for the 12 subcarriers which minimises the effect of the third-order intermodulation products. The following analysis shows that the optimum case is when the frequency of the lowest-frequency subcarrier is about 1 MHz.

The frequencies of the twelve subcarriers can be written as shown below (the spacing between the subcarriers is 295 kHz):

$$\text{frequency of subcarriers} = f_0 + n\ (0{\cdot}295)\text{MHz} \qquad n = 0, \ldots 11 \qquad \ldots 1)$$

The amplitude of each subcarrier is proportional to its frequency. The lowest frequency subcarrier is therefore the smallest, and the most vulnerable to third-order intermodulation products.

The third-order intermodulation products from two coherent signals with frequencies f_1 and f_2 lie at $2f_1 \pm f_2$ and $2f_2 \pm f_1$. There is also the case when three signals are involved and the products lie at $f_1 \pm f_2 \pm f_3$. In general, the amplitude of the intermodulation products is proportional to the product of the amplitudes of the intermodulating signals. This formula is not rigorous, since it depends on the type of non-linearity in the system. However, for the types of non-linearity encountered in an f.m. system, it is reasonable to assume that this formula applies.

It can be shown that, for the twelve subcarriers, the largest intermodulation product that lies at the lowest subcarrier frequency f_0 is produced by intermodulation between three of the other subcarriers. The frequencies of the three subcarriers are $(f_0 + 5 \times 0{\cdot}295)$MHz, $(f_0 + 6 \times 0{\cdot}295)$MHz and $(f_0 + 11 \times 0{\cdot}295)$MHz. The intermodulation product at f_0 is formed by summing the first two frequencies and then subtracting the third.

Since the amplitude of the subcarriers is proportional to their frequency, the amplitude of the intermodulation product is given by:

amplitude of largest intermodulation product at f_0

$$= k(f_0 + 5 \times 0{\cdot}295)(f_0 + 6 \times 0{\cdot}295)(f_0 + 11 \times 0{\cdot}295) \ldots 2)$$

where k is a constant, which depends on the degree of non-linearity.

Hence the ratio between the amplitude of the lowest-frequency subcarrier at f_0 and the largest intermodulation product at f_0 is given by:

$$\frac{\text{amplitude of subcarrier at } f_0}{\text{amplitude of largest intermodulation product at } f_0}$$

$$= \frac{f_0}{k\ [f_0^3 + 6{\cdot}49 f_0^2 + 13{\cdot}14 f_0 + 8{\cdot}47]} \qquad \ldots 3)$$

The optimum set of frequencies for the subcarriers is when the above expression is a maximum and its inverse is a minimum. Inverting the expression and differentiating with respect to f_0 we get:

$$\frac{d}{df_0} = 2f_0 + 6{\cdot}49 - \frac{8{\cdot}47}{f_0^2} = \frac{2f_0^3 + 6{\cdot}49 f_0^2 - 8{\cdot}47}{f_0^2} \qquad \ldots 4)$$

By inspection, the differential is zero when f_0 is approximately 1 MHz, which is thereby the optimum frequency for the lowest subcarrier.

HR/VY

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